9

NOTES ON THE GEOLOGY OF THE LORNE DISTRICT, VICTORIA

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Editor's note: This paper has been made available for publication by Mrs A. B. Edwards. The typescript was completed by the late Dr A. B. Edwards. Dr D. E. Thomas and officers of the Mines Department of Victoria prepared the accompanying maps embracing Dr Edwards's field observations. His clay model was photographed by Mr A. A. Baker.

Introduction

The area under consideration is that part of the Otway Ranges between the sea and main water parting of the Ranges, centred on the township of Lorne (Fig. 1). It comprises especially the parishes of Lorne and Kaanglang, and part of the parish of Wongarra, in the county of Polwarth. Some reference is made to the country bordering this area (Fig. 2).

The rocks of the area are fresh water Jurassic sandstones (arkoses), mudstones and shales, with some thin, intermittent coal partings, a few inches thick, and occasional local grits and conglomerates, together with Tertiary sands, gravels and clays, mostly of uncertain age, although similar to sands and clays associated with Eocene or Paleocene coal seams at Benwerrin and Eastern View.

Interest centres chiefly in the fold-fault structures affecting the Jurassic and Tertiary sediments, and their bearing on the origin of the Otway Ranges, and in the youthful physiography of the area.

Jurassic Sediments

A petrological study of the Jurassic sediments, which predominate in the area, has been given previously (Edwards and Baker 1942). The chief additional point of petrological interest is the occurrence of occasional isolated lenticles of grit and fine conglomerate, containing fragments of relatively fresh granite, 1 to 2 cm across, and an occasional cobble (5 to 10 cm across) of fresh granite and pegmatite, together with waterworn fragments of Palaeozoic greywackes and vein quartz. These lenticles outcrop in the shore platforms S. of Queen's Park (Lorne), and in the river cliffs below the confluence of the St George R. (Fisher's Cr.) and the Cora Lynn Cr.

Similar grits and conglomerate are relatively abundant at Pt Bunbury (Apollo Bay), where the cobbles are up to 10 cm diameter, and include granite, porphyry, quartz, quartzite and shale.

Calcareous concretions are common in many of the sandstone beds, and are well exposed in the shore platforms, and the rapids of the various streams. Many are 'cannon balls', but in places adjacent concretions have 'coalesced' into irregular elongated forms. They are commonly more resistant than the enclosing rock, and project from exposed surfaces. If quarried loose they leave hollows that develop into pot holes, which appear to be a significant factor in the erosion of the hard beds.

Fig. 1—Area centred about Lorne extending from Pt Castries to the Wye R.

Lenses of massive sandstone up to 100 ft thick occur throughout the area, at various stratigraphic horizons, and without apparent continuity, forming bold bluffs and cliffs along the coast, and steep to vertical sided gorges and cliffs, waterfalls and rapids, along the streams (Fig. 1, 2).

Plant remains are common, but mostly as coalified fragments of wood. Very few identifiable remains have been observed (Medwell 1954), and no significant coal seams, apart from the seam at Skene's Cr., first described by Wilkinson (1864) and Stirling (1901).

Fold-Fault Structures

The almost continuous exposures along the coastline from Pt Castries to Apollo Bay, and the sections along the coastal portions of the valleys of the Erskine, St George, Sheoak, Cumberland, and other rivers, reveal a series of sub-parallel folds in the Jurassic strata, with axes trending at 75° to 85° (true) oblique to the coastline in some stretches, but elsewhere parallel to it (Fig. 1, 2). The folds are spaced at intervals of about 1 m. from syncline to adjacent anticline, and tend to be asymmetrical. This fold system appears to extend for at least 25 m. along the coast, from Pt Castries to Apollo Bay, and possibly beyond.

The best exposed fold is the **George Anticline**. The turnover of this fold is exposed in the shore platform and cliffs immediately S. of the mouth of the St George R., where the fold pitches NNE. at about 15°, and in cliffs along the valley of Sheoak R., about ¼ m. upstream from Swallow Cave. This fold, which strikes at 85° can be traced in a westerly direction for about 3 m., along the easterly trending section of the Cumberland R., until it is lost for lack of outcrops.

The most prominent fold is the **Lorne Syncline**, about 1 m. N. of the George Anticline. This syncline strikes at 75°, converging on the George Anticline westwards and is responsible for the location of Loutit Bay (Brough Smythe and Couchman 1874). It can be traced for about 4 m. WSW. of Lorne township, beyond which point it appears to die out in an area of massive flat-lying sandstone. In an ENE. direction the southerly dip of the beds forming the N. limb of the syncline continues unbroken, except for occasional small dragfolds, to beyond Pt Castries. The fold appears to continue, diminishing in intensity, in the Tertiary sediments as far as the Painkalac Cr. (Airey's R.).

Along most of its course W. of Lorne it is asymmetric. Beds in the N. limb dip at 10° to 15° SSE., whereas beds in the S. limb, adjacent to the axis, dip at 40° NNW. This dip flattens to about 20° about ½ m. back from (SE. of) the axis. The turnover of the fold is poorly exposed in the steep valley wall of the St George R., E. of Allanvale farmhouse, along the Artist's Glen track, and it is possible that its axis may in part be a fault.

At intervals of about 1 m., and 1½ m. respectively, N. of the Lorne Syncline, occur changes of dip indicative of an anticline and a syncline. These can be traced along their strikes by infrequent exposures, for about 2 m. (Fig. 1). Eastwards they converge, and die out in the massive, gently SSE. dipping sandstones that form the Erskine R. rapids.

Further to the N., after an interval of about 2 m., in which the beds strike at 70° to 80°, and dip 10° to 15° SE., the dips in road cuttings along the Lorne-Dean's Marsh road, and in exposures in the Little Erskine R. and Stony Cr.—on opposite sides of the road—indicate the likely presence of first an anticline, and then ½ m. further N., another syncline, both striking at about 80°.

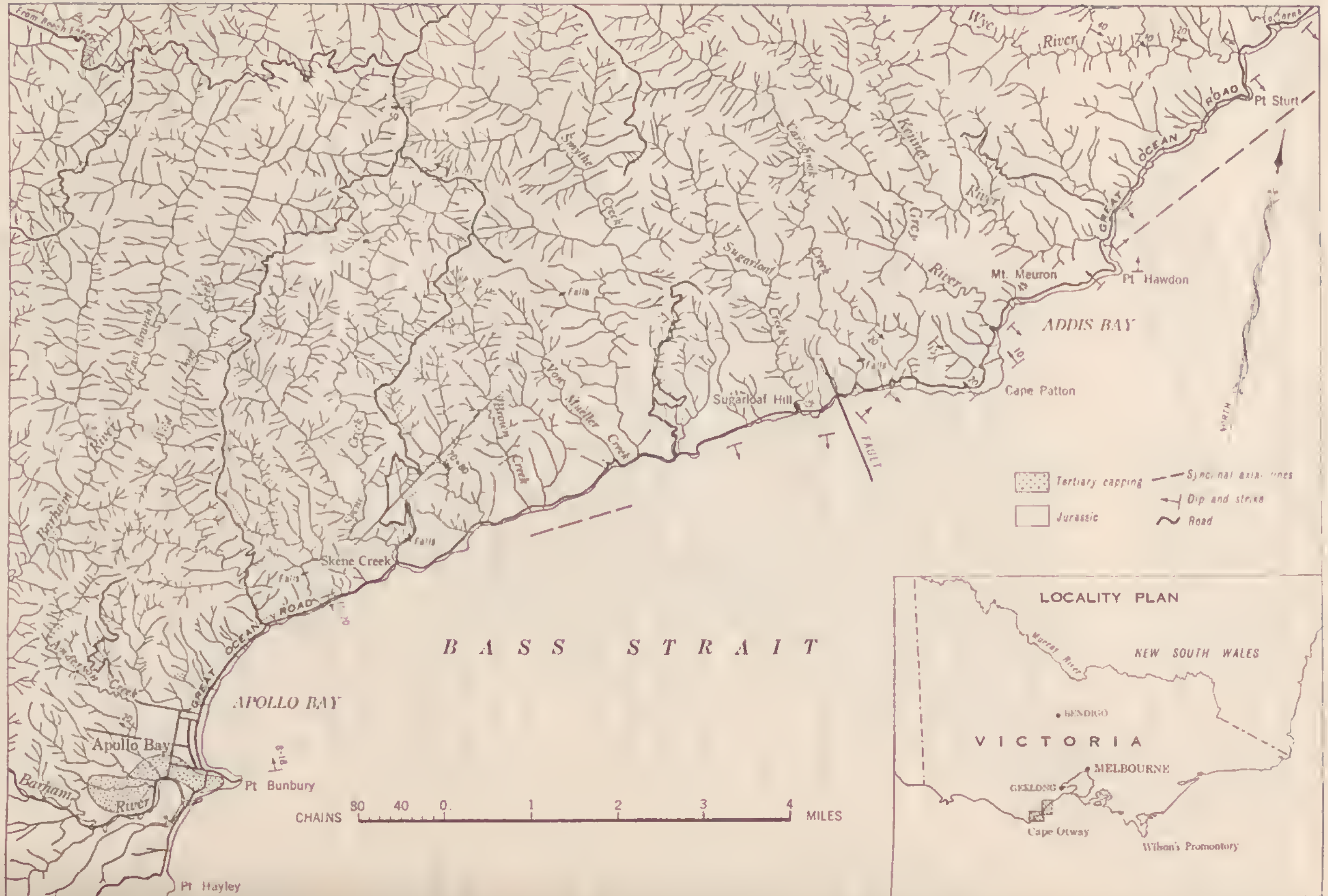

Fig. 2—Area S. of Fig. 1 extending from the Wye R. to Apollo Bay.

The succession of folds is interrupted at the mouth of the Cumberland R., where the beds E. of the river mouth strike at 130°, and dip at 5°-20° NE. The abrupt change of dip and strike implies a fault striking at about 300° across the river mouth, but not exposed.

Continuing along the coast towards Mt Defiance, the strike reverts to 70°, with no break in the beds, and the dip increases to 30°-45° NW. Between here and Mt Defiance corner, a sharp anticlinal fold, the **Mount Defiance Anticline**, is exposed in the road cutting and the sea cliffs. The beds forming the S. limb dip at 70°-90° SE., while those in the N. limb dip at 30°-35° NW. The steeply dipping beds are exposed in the shore platforms, and at Mt Defiance, in the road cuttings, and the turnover of the fold can be seen at two places in the cuttings and the cliffs. The beds at the turnover are somewhat crushed, so that in the shore platforms they are represented by a deep channel. E. of Mt Defiance the fold pitches at about 10°-15° to the E. The vertical movement on this asymmetric anticline or monocline exceeds 250 ft downthrow to the SE. at Mt Defiance.

This anticline can be traced south-westwards along its strike for about 2 m., to beyond Jamieson's Cr. Exposures along the critical section of Jamieson's Cr. are poor.

SW. of Mt Defiance the coastline trends at an angle of about 30° to this anticline, and the dip declines to about 50° SE. at the mouth of Jamieson's Cr. Beyond Jamieson's Cr. the strike of the beds swings round from 70° to 40°-55°, parallel to the coast, with the dip declining to 30°, and then to 25° at the mouth of the Wye R.

From Pt Sturt (Wye R.) to the mouth of the Kennet R. the coast is parallel to the strike of the beds, which dip about 20° seawards.

The mouth of the Kennet marks a syncline (or possibly a fault) apparently striking at about 70°, Pt Hawdon forming the S. limb of the fold, with a dip to the NE., so that the syncline pitches gently in a north-easterly direction. NE. of the mouth of the Grey R., at the head of Addis Bay, the beds are traversed by a strong NW. trending fault. Beds NE. of the fault strike at 135°, and dip NE. at about 20°; beds SW. of the fault strike at 70°, and dip about 20° to the SE.

A second syncline, or more probably, the faulted extension of **Kennet River Syncline** outcrops between the Grey R. and Cape Patton. This syncline also strikes about 70°, and pitches gently to the NE. Its S. limb is exposed to a point 100 yds or so W. of the mouth of Carisbrook Cr., where it is truncated by another NW.-trending fault. The turnover of the syncline is exposed in road cuttings, and the strongly developed N. limb is revealed in the prominent cliff on the summit of Cape Patton, and in the NE. wall of the Carisbrook Falls (Cascades).

W. of the fault the beds strike about 70°, with a seaward dip of about 15° as far as Von Mueller Cr. These beds probably represent the N. limb of the **Kennet River** or **Cape Patton Syncline**, stepped SE. by the Carisbrook fault.

The Von Mueller Cr. marks a strong fault trending about N20°W. W. of the fault the beds strike at 340°, and dip 15° to 25° to the SW. The dip is clearly exposed in a prominent inland cliff parallel to the coast, and in the shore platforms, which expose a minor shallow syncline pitching to the SW.

A second sub-parallel fault trends along the next major creek to the W., bringing a reversion of the strike to 70°, with a seaward dip of 15°-20°, and this trend is maintained, with slight local variations, to the mouth of Wild Dog Cr. Apollo Bay appears to mark another major syncline, comparable with Loutit Bay (Wilkinson 1865, Brough Smyth and Couchman 1874, Stirling 1901). This **Apollo Bay Syncline** strikes at 70°-75°, and pitches gently in this direction. Pt Bunbury, the S. arm of the bay comprises beds striking at 70°-90°, and dipping at 8°-18° to the N. and NE., and this attitude of dip is maintained at Pt Hayley, but an anticline may intervene near the mouth of the Barrum R. (Murray 1887).

On the N. side of the syncline, about ¼ m. N. of the mouth of Skene's Cr., is a strong monoclinal structure, comparable with the structure at Mt Defiance, and which may be called the **Skene's Creek Monocline**. This structure consists of a belt of thin bedded shales and arkoses, up to ½ m. wide, striking at 50°-70°, and dipping at 70°-80° SE. It has been traced by V. R. Stirling (1901) over a strike length of more than 3 m., from Brown's Cr. to the mouth of Wild Dog Cr. (Fig. 2). The steep dips are well exposed in the successive valley walls, and particularly well in the almost continuous road cuttings of the Tanbryn-Skene's Cr. road. The 3 ft coal seam on Skene's Cr. occurs within this steeply dipping zone.

Southwards from the steeply dipping zone the dip flattens progressively to about 15° in the shore platforms. To the N. also the dips decline to about 30° SE., and the shales are then replaced by thick beds of sandstone which dip at 0°-20° NW., the dip increasing to the NW., so that there is here either an anticline, or a change in dip due to faulting.

A further zone of beds dipping steeply to the SE. (55°-65°) was found by Stirling (1901) a short distance up the Wild Dog Cr. This may be a second monocline or a faulted extension of the Skene's Creek Monocline.

Origin of the Folds

The features of these folds are:—

(a) their more or less parallel strikes,
(b) their relative continuity, remarkable for an area of Jurassic rocks in Victoria,
(c) their frequent asymmetry, with steep dips on their southern limbs,
(d) their tendency to die out as they approach thick bodies of massive sandstone.

They appear to be the product of compressional stresses acting on sediments of varying competence.

The fold structures have influenced the form of the coastline, which trends parallel to their strike. In the vicinity of Mt Defiance the coast coincides with a steep limb of a very asymmetrical anticline (or monocline); and the linear form of the coastline as a whole suggests that the SE. margin of the Otway Ranges is terminated either by a major monocline or fault, to which these folds are subsidiary, or by a series of such structures in *en echelon* arrangement, all with a downthrow to the SE., with successive faults or folds or monoclines stepping to the SE., if traversed in a south-westerly direction.

The folds may indicate a period of orogenic compression during the late Cainozoic, if they extend to the Otways as a whole. In this regard it may be noted here that a steeply dipping monoclinical structure, akin to the Skene's Creek Monocline but throwing down to the N., is exposed in the Laver's Hill-Princeton road about 1 m. W. of Crowes railway siding. If they prove to be restricted to the coastal belt, then a more likely explanation is that they are due to the down-warping that marks the SE. limit of the Otway Ranges. If one pictures the development of a simple steeply dipping monocline in stratified rocks, without any of the strata slipping over one another, the beds on the convex side of the flexure will be in tension, and can be lengthened only by fractures, while the beds on the concave side, must be in compression, and can be shortened only by shear thrusts (Hills 1940A), as may be seen in the Yallourn North Open Cut. In a system of interbedded competent and incompetent beds, the stresses set up by a strong monoclinical warp are likely to be relieved, in part at least, by slipping of the more competent strata over one another, with the development of folds equivalent to drag folds in the less competent strata between them. In a series of lensing formation such 'drag folds' would tend to die out on approaching a lens of competent strata; and some deflection of the strike of the fold, away from parallelism to the monocline, might be expected from a fortuitously irregular distribution of the lenses of competent strata.

Shallow minor synclinal dragfolds subsidiary to the larger 'drag folds' occur in the shore platforms SW. of Big Hill Cr., SW. of Pt Grey, and SW. of Von Mueller Cr.

Faults

Numerous dip faults, trending more or less normal to the coastline intersect or displace the fold-fault structures. These faults are either visible in the shore platforms or are inferred from abrupt changes of strike that coincide with notably linear valleys, like Brown's Cr., E. of Skene's Cr.

Most of the exposed dip faults strike NW. to N. displacing the folded strata horizontally, and with a tendency for the SW. block to move SE.

The majority of the exposed faults have relatively small displacements, and none is comparable with the major scarp-producing faults that bound individual fault blocks in S. Gippsland.

Tertiary Sediments

Gravels, sands and clays, with occasional bands of 'ironstone' or ferruginous sandstone of indefinite Tertiary age outcrop at a number of points in the area (Fig. 1). Their presence is commonly indicated by white quartz sand, or by numerous coarse grains of quartz in the soil, a feature not shown by the soils on the Jurassic rocks.

The best exposure of these rocks is in a quarry about 150 yds W. of the pressure reservoir at the head of William St, Lorne, on the road to Erskine Falls. A thickness of about 30 ft of gravels, with intercalated clay bands, is exposed in section in the quary. The gravels are bedded, with some current bedding. They strike at 100°, and dip at 15°S. A further good exposure is in the quarry on the E. side of the Dean's Marsh-Lorne road, between Benwerrin and the turn-in road to the Benwerrin Colliery. Other good exposures are in shallow borrow pits on the spur above N. Lorne, and along the ridge SW. of Big Hill Cr.

These gravels are composed predominantly of white quartz, with some bluish to black quartz and pebbles of quartzite, some of which carry quartz veins. The larger pebbles, in particular, are well waterworn, as is much of the finer-grained quartz, but in some of the gravel exposures the quartz grains are angular, but surprisingly well sized, pointing to derivation from a weathered granitic source without undue wear in transport.

The gravels and sands are more strongly developed along the coastal margins than on the ridges in the interior of the Otway Ranges, or along the divide, except to the N. of Benwerrin and in the vicinity of the Benwerrin Colliery. They occur, moreover, at various levels. Some cap ridges and hill tops, as along the road to Teddy's Lookout (430 ft), and near the summit of Mt St George (650 ft), but others occur well below the summits of adjacent hills composed of Jurassic rocks, as at N. Lorne, and along the track to Allanvale, so that they appear to fill depressions in an older post-Jurassic surface, or have been affected by the relatively recent earth movements.

At Benwerrin Coal Mine, 300 ft below the summits of the adjacent hills composed of Jurassic sediments, they owe their preservation to faulting. Whitelaw (1900) has reported the presence of marine fossils in sands at this locality (the former Great Western Colliery).

At Cape Patton comparable sands are exposed in section along a prominent N.-S. cliff, a short distance inland from the coast, at a height of 580 ft above sea-level. These sands are at a slightly lower elevation than the Jurassic sediments immediately to the N. and S. of them, and lie adjacent to the axis of the Cape Patton syncline in the Jurassic rocks. The stratification of the Tertiary sediments is poorly exposed, but they appear to have the same general dip as the underlying Jurassic beds. Fossils of Eocene age are reported to occur in these beds (Stirling 1901, p. 7; Hall 1909, pp. 103-104), but no fossils were found during the present examination.

Similar, but non-fossiliferous, sands form a capping to the Eagle's Nest cliff, at 360 ft above sea-level, E. of Skene's Cr., and Pt Bunbury, at 60 ft above sea-level (Stirling 1901).

Eastern View Coal Measures

Tertiary sediments of Paleocene or Eocene age (Raggatt and Crespin 1952, Cookson 1954) are exposed at Eastern View along the coast and cliffs, and in the creek sections from about Spout Cr. (E. of Pt Castries), eastwards as far as Painkalac Cr. (Airey's R.). Their contact with the Jurassic sediments is not exposed on the beach, but the uppermost Jurassic sediments exposed are heavily impregnated with limonite. The strike and dip of the Tertiary beds are close to those of the Jurassic sediments, indicating that both formations have been affected by the same earth movements. The contact, however, must be unconformable.

About 50 ft above the base of the Tertiary sediments, as exposed on the beach, is the lowest of a series of 5 thin seams of brown coal, each from 2 to 3 ft thick. They strike 45° and dip at 20°SE. Analyses have been made of 3 of these seams, with the results shown in Table 1.

Table 1
Proximate Analyses of Eastern View Coal Seams

	1	2	3
Moisture, as received	5·12	6.57	15·11
Volatile matter	14·13	17·14	33.93
Fixed carbon	12·15	14·98	35·34
Ash	68·60	61·31	15·74
	100·0	100·0	100·0

1 Lowest seam outcropping on beach, Eastern View
2 Third lowest seam outcropping on beach, Eastern View
3 Fourth lowest seam outcropping on beach, Eastern View.

Overlying the coal seams are two brown ironstained beds of sandy siderite, each about 2-3 ft thick. These consist of fragments of felspar (kaolinized), quartz, chert, granophyre and shaly rock in a matrix of about 50% siderite. The siderite forms encrustations about individual mineral grains and fills interstices.

Inland the extension of these coal seams is masked by sand dunes, but Krause (1874) has suggested that they may represent the continuation of the two seams of brown coal exposed in workings on the Coalmine Cr. (the Stony Cr. of Krause's report). These workings have collapsed but, according to Krause, the upper seam, which was 5 ft thick, was 50 ft above the lower seam, which was 15 ft thick, and was about 50 ft above the Jurassic surface. A thin leaf bed occurred 20 ft above the top of the lower seam. The upper part of the 15 ft seam, as exposed in the shaft, consisted of shaly brown coal overlying a central portion of more compact nature. Below this the coal contained intercalations of sandy shale. The contact of the Tertiary sands and the underlying Jurassic was exposed further upstream.

At present a seam of somewhat sandy brown coal about 5 ft thick, with clay partings, is exposed on the NE. side of Coalmine Cr., about 100 yds upstream from the Ocean Road, with a 2 ft thick bed of ligneous clay about 20 ft above it. Both coal seam and ligneous clay strike at about 80° and dip 30° to the S., as do the Jurassic strata a short distance further upstream. The contact between the Tertiary sediments and the Jurassic is partly hidden by land slips.

Overlying the coal seams is a considerable thickness of whitish sands, clays and ferruginous sandstones, exposed by landslides in the sides of Coalmine Cr., and in the cliffed escarpment behind the Eastern View Hotel. These beds all dip at about 30°S.

A further seam of brown coal, several feet thick, outcrops on the shore about 250 yds SW. of the mouth of Mogg's Cr. (about opposite 'Blue Waters', the third house W. of the Creek). This seam overlies a bed of ferruginous sandstone, which outcrops at normal low tides, and dips seaward. The coal seam is exposed only at exceptional low tides, or when sand has been scoured from this section of the coast. The coal burns readily when air-dried.

The microflora of each of these several coal seams are practically identical and are characterized by the rare pollen *Triorities edwardsii* (Cookson 1954), indicative of Paleocene or early Eocene age.

Raggatt and Crespin (1952) have divided these sediments into the Eastern View Coal Measures, extending to the top of the fifth coal seam exposed on the beach at Eastern View, and the Boonah Sandstone comprising the sands and clays, extending from Eastern View as far as Mogg's Cr. In view of the discovery of a sixth seam, with a more or less identical microflora, in the so-called Boonah Sandstone, it seems desirable to discard this subdivision and include all the sediments between Spot Cr. and Mogg's Cr. as members of the Eastern View Coal Measures. Raggatt (pers. comm.) suspects the presence of an anticline between this coal seam and that at Eastern View but I cannot find this anticline and have noted only a uniformity of dips and strikes on this section of the coast.

At Mogg's Cr. there is a sudden change from freshwater to marine sediments, with no very pronounced change in strike or dip. Raggatt and Crespin (1955, p. 108) state that these beds 'dip at 30° on a bearing of 350°', but show them dipping at 30° on a bearing of approximately 145° on their map (Fig. 1). The map is more nearly correct and the strike of the beds is about 80°.

Eastwards from Mogg's Cr. as far as Fairhaven, *Cyclammina*-bearing grey silts and sands, spotted with yellow copiapite are exposed almost continuously in the road cuttings. E. of Fairhaven they pass below reddish clays, which are exposed in the cutting leading to the bridge over Painkalac Cr. (Airey's R.).

In the shore platform between Mogg's Cr. and Fairhaven there is an extensive outcrop of blackish-brown ligneous clay. The clay strikes parallel to the coast, and dips seawards at about 15°. It is only exposed at very low tides and after periods of sand scour. The ligneous clay, which is interleaved with ferruginous sandstones or silts, is studded with nodules and rods of marcasite. The rods are up to 10 mm long and 1 mm diameter, and are pseudomorphous after fragments of wood. The nodules are commonly casts after marine fossils, including *Cyclammina*, and unreplaced remains of *Cyclammina* are also preserved. Freshly broken surfaces of the clay show a faint criss-cross pattern of indeterminate origin.

The outcrop of this ligneous clay extends for about 250 yds, from opposite the highest point along this section of the coast to about opposite the first house at the SW. end of Fairhaven hamlet. The clay matches in all points the ligneous clay outcropping in the case of the cliffs immediately SW. of Anglesea (except that in the outcropping ligneous clay at Anglesea the marcasite bodies are converted to limonite) and the ligneous clay at the lower half of the cliffs at Demon's Bluff.

From its situation and its dip it is clear that this ligneous clay is the same formation that outcrops, severely weathered, in the road cuttings, where the marcasite of the ligneous clay is altered to copiapite and limonite.

This ligneous clay represents, therefore, the Anglesea Siltstone Member of Raggatt and Crespin's (1952) Demon's Bluff Formation, of which they state—'a complete section of the Formation is exposed at only one place—between Mogg's Creek and Airey's River. Here, because of its uniform lithology and colour, the Members . . . cannot be identified'.

If this is correct, then the Addiscot Greywacke Member and the Anglesea Siltstone Member are one and the same formation, the Addiscot Greywacke being simply the weathered and oxidized outcrop of the Anglesea Siltstone. The association at Demon's Bluff appears to bear the same interpretation, so that the term Addiscot Greywacke Member should be discarded.

At the E. end of its extent the clay appears to pass beneath a platform eroded in compacted dune sands, with occasional thin beds of conglomerate, which extends almost to the first outcrop of limestone at Airey's Inlet.

The broad gap cut by the Painkalac Cr. masks the relationship between Anglesea Siltstone and the highly fossiliferous marine limestones, and pyroclastics (Angahook Member) that form the cliffs extending E. and NE. from Airey's Inlet. Just W. of Painkalac Cr. they strike at 65°-70° and dip at 5°-10° SE., whereas the limestones at Airey's Inlet dip about 5°-10° NW., so that the Painkalac Cr. appears to occupy a shallow syncline, and the sands and ligneous clays appear to pass beneath the limestones and the pyroclastics.

The olivine-basalt at Split Pt (Airey's Inlet) forms the neck of an old volcano, and is surrounded by, and intrusive into, pyroclastics which comprise beds of varying thickness of ash, lapilli and agglomerate, severely weathered, but preserving much of their original texture. Ejected blocks of olivine-basalt, up to 3 ft across, occur at frequent intervals in most of the pyroclastic beds, which have a general northerly dip, and are cut in one or two places by dykes or 'sills' of basalt. Many of the ejected blocks are still glassy, with a ropy texture. Associated with them in places are smaller blocks and fragments of thin-bedded to finely current-bedded siltstones, derived from deeper-lying Tertiary sedimentary formations. They are petrographically distinct from the Jurassic arkoses, and so are presumed to be derived from the Anglesea Siltstone, or from Tertiary sediments of comparable age.

The limestones overlie the pyroclastics in the cliff sections, the two being separated by an impersistent bed of conglomerate, made up of waterworn basalt boulders, capped by 1-6 ft of horizontally bedded vari-coloured sands, which are iron-stained, and carry a proportion of ilmenite. In places they appear ligneous.

Near the major rock stone stack forming Split Pt the limestones come down to the shore platform, giving the platform a distinctive rough to jagged surface, as a result of solution benching processes, but a narrow width of the pyroclastic beds exposed N. and E. of the columnar basalt forming the base of the main stack establishes its plug form.

The limestone sections of the cliff are marked by conical sink-holes, largely filled with ferruginous clays.

Benwerrin Coal Measures

Coal seams of Paleocene to early Eocene age, characterized by a *Triorites edwardsii* microflora (Cookson 1954), occur intercalated with sands and clays in a down-faulted block about 2 m. N. of Benwerrin (Fig. 1). The Tertiary beds are up to 300 ft thick, and cover an area of about 150 acres. Their base is 300 to 350 ft below the Jurassic sediments capping the surrounding hills, and they lie directly on the Jurassic sediments.

The coal seams outcropped in the bed of Box Cr., a tributary of Grassy Cr., which crosses the Tertiary formation in a general southerly direction, and a series of 10 bores put down by the Victorian Mines Department in 1942, reveal that over an area of about 20 acres the sands and clays contain from 1 to 3 seams of coal (Kenny 1947). The upper 2 seams are from 6 in. to 3 ft thick; the lowest seam is 7 to 9 ft thick, and underlies an area of about 10 acres, in which it dips at 1 in 11 to the S. It has been worked intermittently on the N. side of this area, firstly by the Great Western Colliery, which between 1901 and 1903 produced 6,850 tons of coal, and then from 1943 to 1948 by the Benwerrin Colliery, which produced a further 4,544 tons. Reserves were estimated in 1942 as 75,000 tons.

Whitelaw (1900) reports the occurrence of marine fossils, regarded by Dennant as Eocene, in the sediments cut in a shaft sunk about 5 to 10 chains NW. of the workings of the Great Western Colliery. This shaft passed through 112 ft of sands and clays overlying a 9 ft thick coal seam, which rested almost directly on the Jurassic strata. No further marine fossils were found in the mine workings, which entered the seam by edits, where it was under only shallow cover.

The workings of the Great Western Colliery are inaccessible, but three new entrances to the lowest or main seam have been made since 1943 in the Benwerrin Colliery. The most south-westerly of these new workings consisted of 3 bords driven on level course, and 2 cross bords on the dip, with 40 ft pillars, but the roadways collapsed before the pillars were extracted. In these workings the main seam is 8 ft thick. The upper 18 in. contains numerous thin lenses of sandy clay, intercalated with lenses of vitrain (logs), and was not mined. Above this is 4 ft of white clay, with occasional lenses of vitrain, showing growth rings, and clearly derived from isolated logs of wood, compacted about 50% of their original thickness. Above this is a second seam, only 12 in. thick. The dip of the seams was to the NW. at about 1 in 20, and the coal showed a closely spaced cleat trending a little E. of N.

The second entrance was made north-westwards, from the W. bank of the S.-trending branch of the creek, between its junction with the E.-trending branch and the old workings of the Great Western Colliery. In 1948 it had entered about 100 ft, and 3 bords had been established on the dip, with 2 cross bords on level course, separated by 40 ft pillars. Here the main seam was 6 ft thick, with a distinct cleat striking E. of N., and a dip of about 1 in 20 to the NW. The area of available coal was limited, however, by the proximity of the old workings, and a bore 5 chains to the NW. showed only 18 in. of coal, although Whitelaw (1900) records 9 ft of coal in a single seam in the old shaft several chains further NW.

The third entrance was an incline on the dip trending parallel to the inclined tramway to the bunkers, on the S. side of the creek, at the junction of the two branches. The seam here was 7 ft thick, and dipped to the S., so that either the seam is faulted along the easterly trending branch of Box Cr., or it is folded into a gentle anticline pitching flatly to the W.

The Benwerrin coal seams are black, with a brown streak, and correspond to the *Glanzbraunkohle* of German classifications. The main seam, as exposed in the various workings of the Benwerrin Colliery, consists largely of alternating bands, up to 12 in. thick of bright and dull coal, corresponding more or less to clarain and durain. Two fusain-rich bands, each about 2 in. thick, occur in the central part of the seam, and 'crusts' of fusain about 0·25 in. thick occur about cores of

TABLE 2

Analyses of Benwerrin Coal Seams

	1	2	3	4	5	6	7	8
Moisture	31·68	19·36	29·85	30.4	33·4	—	—	—
Volatile Matter	26.73	16·81	30·05	27·3	26·7	—	—	—
Fixed Carbon	35·59	17.79	35·55	33·2	28·2	—	—	—
Ash	6·00	46·04	4.55	9·1	1.7	4·12	4·82	—
Dry, ash-free basis:								
Volatile Matter	42·9	48·6	45·8	45·1	41·2	44·2	46·3	36.4
Carbon	—	—	73·70	73·7	72·0	—	—	—
Hydrogen	—	—	4·76	4.75	4·65	—	—	—
Nitrogen	—	—	1·02	1·0	1·05	—	—	—
Sulphur	—	—	—	0·35	0·5	—	—	—
Oxygen	—	—	20·33	20·2	21.8	—	—	—
Calorific Value (B.t.u. per No.)	11600	—	11930	11540	12535	—	—	—

1 No. 1 or Top Seam (Kenny *Min. Geol. Jour.* 3; 1, 1947: 12)
2 No. 2 or Middle Seam (Kenny *Min. Geol. Jour.* 3; 1, 1947: 12)
3 No. 3 or Main Seam, NE. workings, Benwerrin Colliery, run-of-mine (Edwards *Proc. Aus. I.M.M.* 140, 1945: 210)
4 No. 3 or Main Seam, NW. workings, Benwerrin Colliery (Brown *Min. Geol. Jour,* 3; 4, 1948: 10)
5 No. 3 or Main Seam, S. workings, Benwerrin Colliery (F.F. Field, Mines Dept, Victoria, 1950)
6 Vitrain, composite sample from Main Seam (Edwards *Proc. Aus. I.M.M.* 140, 1945: 242)
7 Dull caol, or durain, from Main Seam (Edwards *Proc. Aus. I.M.M.* 140, 1945: 242)
8 Fusain, from Main Seam (Edwards *Proc. Aus. I.M.M.* 140, 1945: 242)

vitrain, 0·5 in. thick, in the top 12 in. of the seam. Vitrain, derived from logs and branches of wood, still showing growth rings, forms lenses throughout the seam.

Analyses of the coal are shown in Table 2. Ranked in terms of vitrain analyses, this coal can be classed as sub-bituminous, and intermediate in rank between the Triassic Leigh Creek coals of South Australia, and the Permian Collie coals of Western Australia (Edwards 1950).

Physiography

The area is one of youthful physiography, which is most apparent in the form of the streams. Of the rivers, only 4—the Kennet, Wye, St George and Erskine—have valley tracts; and the longest of these, that of the Wye, is less than 1 m. long.

The beds of massive arkose have given rise to rapids where streams cross them on the dip slope. The rapids on the Erskine below its confluence with the Little Erskine are about 50 yds wide and 400 yds long, and rapids extend up the Little Erskine for about ½ m. Rapids up to 30 yds wide and 300 yds long occur on the St George R. below its confluence with the Cora Lynn Cr., and the Cora Lynn Cr. itself, cascades down a series of steep rapids near the head of the Cora Lynn bridle track, as does the Carisbrook Cr. about ¼ m. above its mouth. Lesser rapids occur along the Sheoak and Cumberland R., and most other streams flowing over the Jurassic rocks.

Where massive arkose beds are horizontal, or dip upstream, headward erosion has given rise to waterfalls with vertical drops of from 20 to 100 ft, and short steep-sided to vertical walled gorges downstream, as on the Sheoak and St George R. Such features are common to the area, and to the Otway Ranges generally. The arkose beds constitute a series of temporary base levels, and upstream from such a waterfall it is not uncommon for a valley to widen, and possess a small bouldery flood plain.

An outcome of the rapid down-cutting of the streams, combined with the occurrence of lensiform beds of massive arkose, 50 to 200 ft thick, at various stratigraphic horizons, is the development of meanders set in deep cliffed amphitheatres, where a stream has been superimposed on the massive arkose beds, and has cut its way round, rather than through, the lens of arkose. A beautiful example, presenting a combination of gorge, waterfall, meanders, cliffed amphitheatre, temporary flood plain and imminent domestic piracy is provided by the St George R. (Fisher's Cr.) immediately upstream from its confluence with the Cora Lynn Cr., about ½ m. above Allanvale bridge. Pl. X shows these features modelled approximately to scale in clay.

Upstream from the junction of the two streams the St George flows through a short gorge with nearly vertical sides, formed by the headward erosion of the Phantom Falls, which have a drop of about 60 ft. Above the falls the stream flows on the surface of a massive arkose bed, meandering in a bouldery flood plain that is bounded on the S. by a cliffed amphitheatre with walls 100 to 200 ft high, and a radius of about 200 yds. About 1 m. further upstream the St George R. (Fisher's Cr.) approaches within ¼ m. of the Cora Lynn Cr. At this point the Cora Lynn Cr. lies about 100 ft below the outer (convex) side of a large meander of the St. George R. through its temporary flood plain. The divide between the two streams is about 100 ft E. of the St George R., and less than 20 ft above its normal level, so that a severe flood or cloudburst in the upper reaches of the St George could cause it to break through to the Cora Lynn at this point.

The straight and deeper, uninterrupted SE.-trending course of the Cora Lynn Cr. suggests that it flows along a fault, but there is no sign of the fault below its confluence with the St George R., where the extensive rapids give place to a sharp bend to the E., fronted on the S. by vertical cliffs, marks a stage in the development of another cliffed amphitheatre.

The cliffed bends of the Erskine R., downstream from the Erskine Falls, mark a more advanced stage in the development of a cliffed amphitheatre. Below Allanvale bridge the St George shows a further development of pronounced meanders in cliffed amphitheatres.

The gorge extending upstream from the mouth of the Cumberland R. shows sharp bends with vertical walls. At its mouth it appears to follow the course of a fault, but upstream it appears to have developed by headward erosion through massive flat-lying arkose beds. The vertical sides of the gorge are due largely to the undercutting of the massive arkose in a bed or beds of mudstone at the base of the arkose. The gorges, waterfall, rapids and bends of the Sheoak R., as far upstream as the Swallow Cave, are mainly formed in response to headward erosion from a sea-cliff.

Dry Valleys

Dry valleys occur at several places, and are due to varied causes. A truncated dry valley with gently sloping walls extends from the valley of the Cumberland R. in an easterly direction on the N. side of the two hills known as the Brothers, encountering the coastal cliffs some 30 ft above sea level, a little to the W. of the Sheoak Cr. mouth. Hall (1909, p. 97) suggests that this was the original mouth of the Cumberland, which now flows past the cut-off end of its old bed, about 100 ft below it. Presumably this is the result of piracy by a smaller stream cutting back from the coastal cliffs, possibly along a fault.

The high sea cliffs immediately W. of the mouth of Big Hill Cr. mask a deep gorge-like hanging valley whose headward end has been destroyed by marine erosion. The landward wall of this dry valley is a vertical cliff more than 100 ft high. On the seaward side a narrow razorback, with vertical sides, separates it from the sea. The 'mouth' of the valley is about 60 ft above sea level. It must once have been occupied by a stream at least as large as Big Hill Cr., and its preservation as a hanging valley points to a considerable recession of the sea cliffs along this part of the coast.

Three peculiar dry valleys occur to the SW. of Phantom Falls. The track from Phantom Falls to Henderson's Falls passes through two of them, the more 'dramatic' of which is known as the 'Canyon'. The third valley is about 200 yds S. of the Canyon and parallel to it.

The Canyon is about 200 yds long, and trends across a ridge between two streams, at right angles to the axis of the ridge and the streams. At its E. end it is a cleft about 30 ft wide with vertical walls 30 ft high, and it widens and shallows towards the W. end. The floor consists of huge angular blocks of arkose piled irregularly on each other, so that it appears to be a collapsed cave. A remnant of the roof remains at the E. end. Caves on such a scale are unusual in the Jurassic rocks, but one such cave occurs some distance above sea level at Cape Patton, and a collapsed cave (The Devil's Punch Bowl) is known on the S. coast of the San Remo Peninsula (Edwards 1942). The Swallow Caves, above the Sheoak Falls, may represent similar caves truncated by headward erosion of the Sheoak

Falls and rapids, but may be due chiefly to undercutting by the river in flood. Small sea caves occur in the cliffs W. of the Cumberland R. and at the foot of Big Hill.

The dry valley just S. of the Canyon is about twice as wide, and somewhat deeper, with similar vertical walls and a floor composed of angular blocks.

The third of these dry valleys cuts across the next ridge to the SW. Its E. end is high above the present streams, but its W. end leads down to Henderson's Cr. The track follows down the centre of it, between steep to vertical walls. This valley is due, in part at least, to erosion by running water.

It is suggested that these valleys originated as caves through the solution of calcite from zones of highly calcareous arkose, such as occurs in parts of Gippsland (Edwards and Baker 1942, p. 205).

Drainage Pattern

Two directions dominate the drainage pattern—a SE. direction, approximately normal to the divide of the Otways, and commonly following a dip slope; and an E. direction (about 80°), approximately parallel to the fold axes, tending to develop where massive arkose is encountered. Many streams show both trends. Easterly trends are less in evidence W. of Cape Patton than E. of it.

Skene's Cr., Wild Dog Cr. and the Barrum R. flow almost due S. in their upper courses.

Coastline

The coastline from Pt Castries to Apollo Bay falls into two sections. As far as Cape Patton it consists of cliffs up to 300 ft high with a steeply sloping hinterland, fronted by flat rock platforms that rise abruptly above low tide-level, with occasional interruptions by stretches of sandy beach, at the mouths of the bigger streams. The major sections of beach coincide with synclinal structures.

From Cape Patton (actually Sugarloaf Hill) to Apollo Bay, there is a narrow coastal plain rising 20 to 40 ft above sea-level, backed by steep hills, and marking a relatively recent emergence. Traces of this coastal plain can be detected at Pt Hawdon, Pt Sturt, Pt Grey, and possibly at Mogg's Cr., on the Pt Castries side of Cape Patton. The seaward edge of the coastal plain is generally marked by low cliffs, and rock platforms similar to those nearer Lorne, and occasionally by sand dunes.

The general trend of the coastline is SW., in a series of nearly straight lines, stepped out *en echelon* to the SE. going south-westwards. These steps, of which the most marked are at Loutit Bay (Lorne) and Apollo Bay, coincide with synclinal structures.

For most of its length the rocks dip seawards, and the shoreline parallels the strike of the beds, but for short stretches between the Erskine and St George R., between Pt Hawdon (Kennet R.) and Carisbrook Cr., and also at Pt Bunbury, the dip is inland.

NE. of Pt Castries, where the Jurassic rocks give place to soft Tertiary sediments the cliffs are weathered back and tend to be fronted with sand dunes and long stretches of beach, broken only by the harder rocks of Split Pt at Airey's Inlet, and by lesser outcrops of ferruginous sandstones at about low tide level.

The rock platforms W. of Pt Castries have been described in detail elsewhere (Edwards 1951; Jutson 1949, 1954). They are interrupted by channels along major joints, faults and crush zones, and are narrowest and least regular in the nearly vertical beds at the foot of Mt Defiance, where the cliffs behind them are highest.

The cliffs and platforms are subjected to active marine erosion, and the smaller streams have difficulty in keeping pace with the erosion, so that they tend to enter the sea by steep cascades.

Formation of the Otways

Two views have been proposed as to the origin of the Otway Ranges. Krause (1874) pictured the Otways as an island in the Tertiary seas, the Tertiary sediments being deposited around its margins. This view has the support of Hall (1909, p. 99), Coulson (1938) and Thomas and Baragwanath (1949, p. 32). The alternative view, proposed by Hills (1940B, p. 267) is that the Otway Ranges were domed up by fault and fold movements late in the Cainozoic, and that their original Tertiary cover has been stripped from them.

Evidence in support of the second view is to be found in the rank of the Benwerrin coals, which are intermediate in rank between the Triassic Leigh Cr. coals of South Australia and the Permian Collie coals of Western Australia (Edwards 1950). Metamorphism due to tectonic and igneous agencies can be excluded, as cause for its relatively high rank, so that the Benwerrin coal must at one time have been buried beneath a considerable cover, because, under such conditions, rank is largely a reflection of depth of burial.

The Benwerrin coal is of as high rank as the brown coal cut in the Wurruck Wurruck No. 1 Bore, at a depth of 2560-2714 ft, and in terms of carbon content is either equal, or somewhat lower in rank than the brown coal at 3610-3633 ft in Bengworden South No. 2 Bore. The comparison is rendered difficult by the high sulphur content of the Bengworden coal—possibly organic sulphur (Edwards 1945, p. 224). This suggests, therefore, that the Benwerrin coal seams were originally buried beneath a cover of not less than 2500 ft of Tertiary sediments, and possibly as much as 3500 ft. The smaller figure is comparable with the total thickness of freshwater and marine sediments extending from the base of the Tertiary at Eastern View to the top of the sequence exposed at Torquay, as computed by Raggatt and Crespin (1952). It may be noted, moreover, that marine fossils occur in the sands above the Benwerrin seam (Whitelaw 1900), which provides proof of some degree of subsidence after the coal was deposited.

Some check on this estimate can be made by plotting the moisture contents of the coal seams cut in the Notown Bore, New Zealand (Wellman 1950) against their depth of occurrence, and the moisture content of the Yallourn seam, against an assumed original estimated cover of 600 ft thickness (Fig. 3). If a curve is drawn through the three points obtained, the approximate original thickness of cover over the Benwerrin seam can be estimated from it. According to the moisture contents of the several reliable analyses quoted in Table 2, it was originally buried to a depth of 2200-2500 ft. An error of ± 500 ft in the thickness of the original overburden of the Yallourn seam would not affect the estimate significantly.

The absence of igneous rocks capable of metamorphosing the coal is a feature of the Otway Ranges distinguishing them from the South Gippsland Highlands. To the E. at Airey's Inlet olivine-basalt volcanic necks and pyroclastics intrude and overlie Eocene sediments (Anglesea Siltstones and Eastern View Coal Measures, or their equivalents), and are unconformably overlain by thin beds of conglomerate and standstone and by Janjukian limestones (Point Addis Member of Raggatt and Crespin 1952).

At Gellibrand and Kawarren, on the opposite side of the Otway Ranges, there are further outcrops of olivine-basalt, as horizontal flows resting on the Jurassic surface, and as necks and dykes which have indurated the overlying Tertiary sands and clays that they intruded. Ligneous clays, upwards of 115 ft thick, containing fossil shells and pyrite (Anglesea Siltstones?) and thin seams of brown coal occur low in the Tertiary sequence, 'possibly below the horizon of the basalt flow in Love's Creek, although the latter rests directly on Jurassic strata' (Kenny 1938, p. 76). Overlying the ligneous clays, and separated from them by 80 to 90 ft of sands and

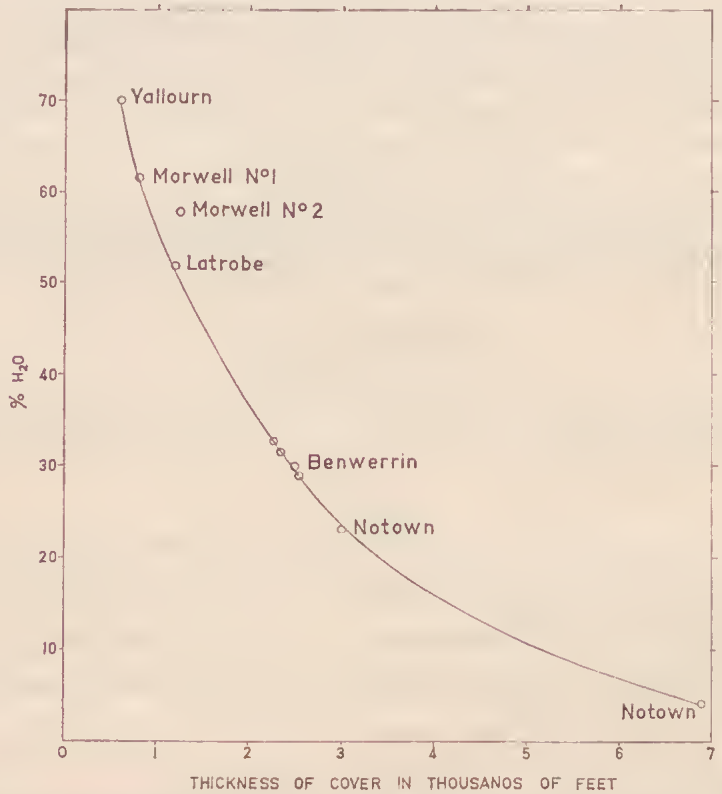

Fig. 3—Relation of moisture contents of coal seams to depth of burial when tectonic and igneous agencies are absent.

clays, is the horizontally bedded Kawarren Limestone, described as typically Janjukian by Chapman (Kenny 1938), with a fossil fauna practically identical with that of the limestone at Airey's Inlet (O. P. Singleton: pers. comm.).

In view of these basaltic occurrences, the absence of basaltic plugs or dykes from the Otway Ranges may mean that the region was not subjected to faulting or related earth movements during the period of volcanic activity.

The physiographic evidence is proof that the Otways were elevated in late Tertiary time, probably the Pliocene, by the processes of faulting and folding that determined the shape of the present coastline. The Tertiary sediments as a whole were warped and folded by these movements, but where adjacent to the Jurassic show only a slight degree of unconformity, so that little or no folding or tilting could have occurred in the Jurassic rocks before the Eocene.

The soft and often unconsolidated nature of the Tertiary sediments would render them liable to rapid removal when subjected to vigorous erosion following the Pliocene elevation. Where Tertiary sediments are preserved within the Jurassic areas they occur in sheltered positions which they owe largely to the effects of the faulting.

The narrow coastal plain extending from Apollo Bay towards Cape Patton points to a further minor, possibly Pleistocene, emergence, which would have rejuvenated the still vigorous erosion resulting from the major uplift.

In the absence of reliable evidence of earlier tectonic movements it can be assumed that any metamorphism of the Benwerrin coal by tectonic forces would have occurred during the Pliocene, but as is apparent in the Morwell district, and particularly in the Latrobe seam, pressure developed during monoclinal folding sufficient to cause considerable overthrusting of the coal seam did not raise it to anything like the rank of the Benwerrin seams.

The forces operating in the Otways were no greater than those in South Gippsland, and probably were weaker. The rank of the Benwerrin coals must be attributed, therefore, to overburden pressure with all that this implies.

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Explanation of Plate

Plate X

Relief model of the area around the confluence of St George R. (R) and the Cora Lynn Cr. (C). Phantom Falls (P) occur at the head of a gorge (G). A cliffed amphitheatre (A) and a flood plain (F) with meanders occur above the falls. A low divide (D) occurs between the St George R. and the Cora Lynn Cr. Horizontal scale approximately 1 in. = 30 chains, vertical scale 1 in. = 100 ft.